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A framework for determining the optimal window-integrated PV panel considering occupant satisfaction, energy performance, and economic feasibility

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ABSTRACT

This study developed a framework for commercializing window-integrated photovoltaic (PV) panels along with overcoming the limitations of existing window system. The developed framework determined the optimal window-integrated PV panel among window-integrated PV panels according to 3rd generation PV panel type and visible light transmittance (VLT) by considering three aspects: (i) occupant satisfaction; (ii) energy performance; and (iii) economic feasibility. The developed framework consisted of three steps. First, data on building and window-integrated PV panel were collected. Second, various window-integrated PV panels were evaluated in three aspects. Third, the optimal window-integrated PV panel was determined through multi-objective optimization.

Keywords: 3rd generation photovoltaic panel; window-integrated photovoltaic panel; occupant satisfaction; energy performance; economic feasibility; multi-objective optimization.

NOMENCLATURE

Abbreviations	
Low-E	Low emissivity
PV	Photovoltaic
VLT	Visible Light Transmittance
VR	Virtual reality

1. INTRODUCTION

Globally, urbanization has resulted in a significant increase in the density of high-rise buildings in various cities for the past few decades. The concentration of high-rise buildings in a limited area within the city has not only increased the energy demand due to the increasing number of occupants, but it also has limited the new and renewable energy generation due to the lack of installation space. In particular, the frequent use of front windows and glass envelopes, including curtain walls, has further increased energy demand along with heating and cooling loads [1]. To sum up, urbanization has caused environmental problems due to urban energy consumption.

Therefore, in order to solve urban problems related to energy, many studies have attempted to improve the performance of windows. First, previous studies have improved the performance of windows in buildings with the goal of energy savings in buildings. In these studies, functional glass such as low emissivity (Low-E) glass or electrochromic glass was applied to windows to reduce heating and cooling loads [2,3]. Lin et al. [2] developed a Low-E glass manufacturing method using spray coating, which is cheaper than the conventional method, and decreased the emissivity by 32.8%, thus reducing the heating and cooling load. Liao et al. [3] developed electrochromic glass that can change color to dark green with an applied voltage and confirmed through experiments that it could reduce heating and cooling loads. Second, existing research has attempted to introduce photovoltaic (PV) panels to windows with the goal of new and renewable energy generation. In various studies, the energy performance of a building was improved via self-power generation as diverse 2nd generation (inorganic) PV panels with high power generation efficiency were applied to the building façade [4–6]. Kang et al. [4] developed a smart PV blind that tracks sunlight in real-time to maximize power generation and evaluated its technological-economic performance. Liang et al. [5] designed a PV louver that maximizes power generation considering the incident angle. Cook and Al-Hallaj [6] developed a double-sided PV structure with increased energy efficiency for BIPV windows.

In summary, the previous studies attempted to improve building energy performance through heating and cooling energy savings and new and renewable energy generation based on improved window systems. However, there were the following limitations. An opaque material was used to improve the high thermal transmittance of the windows. In addition, the existing

PV panels were used separately from windows like louvers or blinds. Consequently, the window with improved energy performance blocked occupants' views and inhibited their sense of openness. As a result, the existing window improvement method helped to improve the energy performance of the building. Still, it caused dissatisfaction among the occupants who spent a lot of time indoors and impaired their quality of life. To overcome these limitations, the use of window-integrated panels in which 3rd generation PV panels are combined with windows is suggested as an alternative [7]. The 3rd generation PV panel, which only absorbs infrared and ultraviolet rays except for visible light for solar power generation, ensures that visible light transmittance (VLT), which determines the window's transparency applied with the panel low [8]. In addition, the VLT of the 3rd generation PV panel can be determined by considering the occupants' preference, insulation, and power generation efficiency [9]. Accordingly, the window-integrated PV panel to which the 3rd generation PV panel is applied can not only achieve heating and cooling energy savings in buildings and new and renewable energy generation, but also increase the occupants' satisfaction with the windows.

However, despite these various advantages, the window-integrated PV panel has not technically reached the commercialization stage due to its lower power generation efficiency than the existing PV panel [10]. This low efficiency serves as a factor that lowers the economic feasibility of the window-integrated PV panel. In addition, a trade-off among VLT, power generation efficiency, and insulation of the window-integrated PV panel leads to a trade-off relationship between occupant satisfaction and building energy performance. Therefore, a quantitative and comprehensive evaluation is needed to commercialize the window-integrated PV panel with significant advantages in terms of occupant satisfaction. Furthermore, the evaluation results are expected to contribute to the commercialization of window-integrated PV panels when used to optimize the occupant satisfaction, energy performance, and economic feasibility of the window-integrated panel. Therefore, this study evaluates window-integrated PV panels in terms of occupant satisfaction, energy performance, and economic feasibility according to the type and VLT of the 3rd generation PV panel and presents a framework for determining the optimal window-integrated PV panel.

2. MATERIAL AND METHODS

This study proposed a three-step framework for evaluating window-integrated PV panels and determining the optimal window-integrated PV panel. The first step is to collect data on the target building and window-integrated PV panel needed to evaluate the window-integrated PV panel. The second step is to evaluate occupant satisfaction, energy performance, and economic feasibility of window-integrated PV panels. The third step is to determine the optimal 3rd generation PV panel type and VLT (i.e., the optimal window-integrated PV panel) using multi-objective optimization.

2.1 Step 1. Data Collection

2.1.1 Building data

The building data were collected because the building is an object to which window-integrated PV panels are applied, and it also affects the window-integrated PV panel. First, the location and orientation data of a building in which the window-integrated PV panel is installed were collected because solar radiation varies depending on the location and orientation of the building, which affects the energy performance of the window-integrated PV panel. Second, the window size data of the building were collected. The area of the window-integrated PV panel and the solar radiation that reaches the solar panel of the building increases as the size of the window increases. In addition, the size of the window affects the occupants' psychological satisfaction [11]. Third, building type data that affect the economic feasibility of window-integrated PV panels, such as national subsidies, were collected.

2.1.2 Window-integrated PV panel data

The window-integrated PV panel data were collected as the subject of this study. First, the types of 3rd generation PV panels with transparency that can be used for window-integrated PV panels were determined: (i) dye-sensitized solar cell (DSSC); (ii) organic photovoltaic (OPV); and (iii) Perovskite solar cell (PSC). The following window-integrated PV panel data were collected according to the VLT for the determined PV panel information. First, capacity and efficiency data that determine the amount of power generation of window-integrated PV panels were collected. Second, price information (i.e., initial cost, maintenance cost, repair cost, etc.) that determines the economic feasibility of the window-integrated PV panel was collected.

2.2 Step 2. Evaluation of window-integrated PV panel

Based on the data collected in Step 1, this study evaluated the window-integrated PV panels in three aspects: (i) occupant satisfaction; (ii) energy performance; and (iii) economic feasibility.

2.2.1 Occupant satisfaction

There is a need to evaluate the level of satisfaction with window-integrated PV panels among occupants who use the window-integrated PV panel in a building. This study examined occupant satisfaction according to the VLT of the window-integrated PV panel through virtual reality (VR). To this end, this study evaluated occupant satisfaction through a survey based on the designed VR experiment.

2.2.1.1 Virtual reality experiment design

Before designing the VR experiment, VR was implemented based on building data. The VR setup implemented based on the actual building data enables iterative experiments in various environments (i.e., VLT) where subjects can be applied to the actual building. Unreal engine and Unity software, commonly used game engines for VR implementation, can be used to implement VR (refer to Fig. 1). In addition, it is possible to implement VR more easily through 3D objects designed via 3D modeling software such as SketchUp, Rhino, and REVIT.

(a) VLT of window = 10% (b) VLT of window = 30% (c) VLT of window = 50%

Fig. 1 Virtual environments according to the different VLT of window-integrated PV panels

Next, the experiment designed in the implemented VR is shown in Fig. 2. First, participants listen to explanations about the process of the experiment and submit their personal information (i.e., age, gender, color blindness, eye disease, etc.) for five minutes. Second, participants wore VR devices for three minutes. Third, participants work freely for five minutes in all VRs implemented according to VLT and then submit their satisfaction surveys.

Lastly, the following should be considered to proceed with the experiment in the implemented VR. First, the VLT of the window-integrated PV panel in VR was set based on the actual 3rd generation PV panels. For example, if there are five 3rd generation PV panels with different VLT values, participants repeatedly experiment with five VRs developed based on them. Next, at least 30 participants should be recruited based on the central limit theorem. As the sample size increases, it follows a normal distribution. Therefore, the larger the number of participants, the higher the statistical reliability of the results. However, there is a limit to the number of participants in this experiment. Therefore, a cross-over design should be adopted in this case. Lastly, the experimental sequence according to the VLT should be randomly arranged to prevent an order effect.

2.2.1.2 Occupant satisfaction questionnaire

This study evaluated participants' occupant satisfaction in VR according to each VLT through two questionnaires. First, the participants' visual comfort depending on VLT was evaluated via a 7-point Likert scale survey. Second, the participants' emotional state was evaluated using the Positive and Negative Affect Schedule (PANAS), a 5-point Likert scale self-report questionnaire [12]. The PANAS comprises 20 items, with 10 items measuring positive affect and 10 items measuring negative affect. The indices of positive affect evaluate the levels of mental stability, vitality, and encouragement felt by the participants in a given environment, while those of negative affect evaluate the feelings of depression, tension, and withdrawal.

2.2.2 Energy performance

The energy performance of window-integrated PV panels was evaluated in order to analyze the reduction of energy consumption in a building, which is the main purpose of the window-integrated PV panel. The energy performance of the window-integrated PV panel was evaluated by subtracting the energy consumption of the building from the energy generation of the window-integrated PV panel, which changes according to the window-integrated PV panel type and VLT.

First, the energy generation of the window-integrated PV panel was calculated. The solar radiation that reaches the window-integrated PV panel was calculated based on the building's location, orientation, and window area data. The energy generation was also estimated considering the capacity and efficiency of the PV panel determined according to the 3rd generation PV panel type and VLT, and solar radiation energy. Second, the building energy consumption was estimated using energy simulation. The solar radiation energy that reaches each building room is different according to the

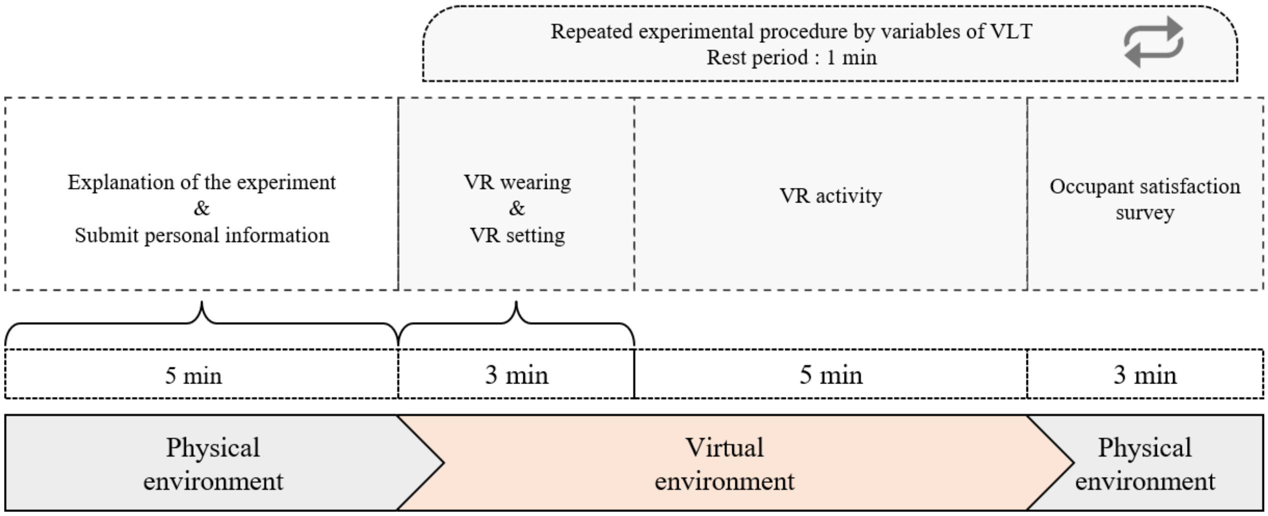

Fig. 2 Timeline of the experimental procedure

building location, orientation, window area data, and the VLT of the window-integrated PV panel. Depending on the solar radiation that reaches the room, the heating and cooling loads of the room change, which in turn affects the energy consumption of the building. The energy consumption can be calculated using *DesignBuilder*, the energy simulation software that uses *EnergyPlus* as its simulation engine.

2.2.3 Economic feasibility

To commercialize the window-integrated PV panels, their economic feasibility needs to be proven. Therefore, this study evaluated the economic feasibility of the window-integrated PV panel via life cycle cost (LCC) analysis.

Prior to LCC analysis, major assumptions were established: (i) analysis approach; (ii) starting point of analysis; (iii) analysis period; and (iv) real discount rate. The analysis approach was selected from among several indicators to evaluate economic feasibility (e.g., net present value (NPV), savings-to-investment ratio (SIR), etc.). The starting point of analysis was set as the point at which window-integrated PV panels began to be applied to the target building. The analysis period was set as the average lifespan of the 3rd generation PV panels. The real discount rate was calculated based on the nominal interest rate and inflation rate.

Next, the benefit and cost factors of window-integrated PV panels were defined. The benefit factor includes the electricity cost of the building reduced through the generation of window-integrated PV panels, whereas the cost factors include the initial investment cost, maintenance costs, and replacement cost. The initial investment cost refers to all expenses incurred from the first application of the window-integrated PV panel to the target building. The maintenance costs refer to any expenses (e.g., repair cost, etc.) incurred when the window-integrated panel is used during the life cycle. The replacement cost refers to any expense required to replace the components of the window-integrated PV panel during the life cycle. Consequently, economic feasibility was evaluated by substituting the benefit and cost factors into the determined analysis approach.

2.3. Step 3. Determination of the optimal window-integrated PV panel

Each window-integrated PV panel according to the 3rd generation PV panel type and VLT was evaluated from the three aspects given in Step 2. A Pareto optimal solution was determined using multi-objective optimization to determine the optimal window-integrated PV panel considering occupant satisfaction, energy performance, and economic feasibility. Before multi-objective optimization, standardization was performed to make the three evaluation results be on the same scale (i.e., minimum and maximum values are 0 and 1, respectively). Next, a Pareto optimal fitness function was established to maximize all three objective functions (i.e., occupant satisfaction, energy performance, and economic feasibility) (refer to Eq. (1)). Lastly, the window-integrated PV panel with the smallest value of the Pareto optimal fitness function was determined as the optimal window-integrated PV panel. However, the weight of each objective function can be set between 0 and 1 according to the potential users' preferences. In addition, it can be said that the 3rd generation PV panel whose value calculated using Eq. (1) is closest to 0 is the optimal window-integrated PV panel.

$$Fitness\ Function\ (i) = \sqrt{w_{OS} \times (1 - S_{OS})^2 + w_{EP} \times (1 - S_{EP})^2 + w_{EF} \times (1 - S_{EF})^2} \quad (1)$$

where, w_{OS} and S_{OS} stand for weight and objective function of occupant satisfaction, w_{EP} and S_{EP} for weight and objective function of energy performance, and w_{EF} and S_{EF} for weight and objective function of economic feasibility.

3. CONCLUSIONS

This study developed a framework to evaluate various window-integrated PV systems and determine the optimal window-integrated PV panel in terms of occupant satisfaction, energy performance, and economic feasibility. It is expected that the application of the optimal window-integrated PV panel determined using the proposed framework will contribute to the urban society as follows.

First, the optimal window-integrated PV panel, which is relatively new compared to the existing BIPV, can be made available publicly and commercialized via this framework. In addition, unlike the conventional PV panels that come in a limited form, such as louvers, the optimal window-integrated PV panel can be applied flexibly in various situations according to the building design.

Second, the optimal window-integrated PV panel can be used as one of the solutions to urban problems related to energy in cities, which undergo difficulties in applying new and renewable energy systems.

Third, it can increase the level of satisfaction with windows among urban dwellers who spend most of their time indoors, which will further improve their quality of life.

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